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Auroral Pulsations from Atmospheric Waves

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22 August 1978

Interim Report

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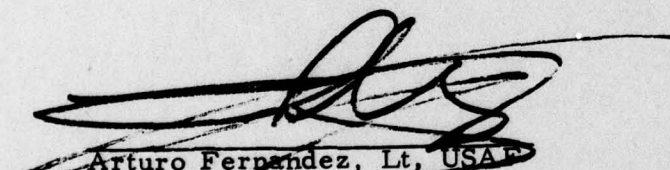
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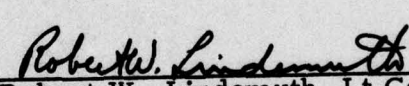
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the phasefront, periodic variations in auroral brightness can result. The pulse shape and magnitude of the pulsations depend on both the energy spectrum and pitch angle distribution of the particles and the amplitude and altitude distribution of the atmospheric waves. This model, which attributes variable precipitation to a temporally changing local loss cone, is in sharp contrast to models which require temporal changes in the particle source above the atmosphere. Many of the observed features of pulsating aurorae can be explained by the present model. It is suggested that the required atmospheric oscillations can be provided by acoustic-gravity waves that are generated by active arcs near the poleward edge of the auroral oval. This mechanism can also produce aperiodic pulsations by convection of irregular atmospheric density fluctuations, which may result from interfering acoustic-gravity wave trains.

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PREFACE

The author wishes to thank J. M. Straus, Y. T. Chiu, B. K. Ching, J. B. Blake, and G. A. Paulikas for enlightening discussions related to this work.

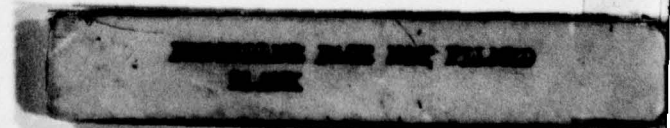
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INTRODUCTION

Several reviewers (Omholt, 1971, Pemberton and Shepherd, 1975, Royrvik and Davis, 1977) have described the observational characteristics of quasiperiodic auroral brightness fluctuations in detail. These authors note that the frequencies at which aurorae are modulated generally fall into one or more distinct frequency bands. Fluctuations at a few Hz, sometimes referred to as flickering, are often superposed on lower frequency pulsations with periods ~ 10 s. The behavior of these two components is independent, indicating that the responsible mechanisms may be different. The fact that the fast pulsations have periods similar to the bounce periods of particles trapped in the high latitude geomagnetic field suggests that the causative processes in this case are magnetospheric in nature. The present report is concerned with the pulsations with periods longer than the particle bounce periods.

A model for the pulsating aurora must explain all of the following observed features:

- 1) quasiperiodic brightness fluctuations having pulse shapes that range from sinusoidal to half-sinusoids which abruptly "switch-on" and "switch-off "
- 2) damped pulsations; irregular pulsations
- 3) Pulse amplitudes of up to 100%
- 4) Pulse periods $\sim 5 - 20$ s (assuming that the frequencies ≥ 1 Hz are caused by a separate phenomenon as discussed above)



- 5) Synchronous pulsation over entire forms of both discrete and diffuse types
- 6) Streaming, or localized bright areas that travel across the auroral forms.
- 7) Forms exhibiting an abrupt onset or cessation of pulsations
- 8) Preferential occurrence of pulsations at the equatorward edge of the auroral oval on closed field lines
- 9) Conjugate pulsations
- 10) Preferential occurrence in the post midnight and morning oval
- 11) A precipitating electron spectrum that varies over the cycle of a pulsation.

The theory of pulsating aurorae that has gained support in recent years is based on the hypothesis that pitch angle scattering of trapped particles into the bounce loss cone by whistler noise is modulated at high altitudes by geomagnetic micropulsations (Coroniti and Kennel, 1970). Recently, the ability of this theory to describe some of the properties of the pulsating aurora has been questioned by experimenters (Whalen et al, 1971, Heacock and Hunsucker, 1977). In particular, Heacock and Hunsucker found that micropulsations appeared to be the effect rather than the cause of precipitation pulsations. A local or atmospheric mechanism related to the ionization caused by the particles was proposed by Maehlum and O'Brien (1968) but they found that exceptionally intense precipitation was required to sustain the self-generated pulsations. Observed pulsations, on the other hand, are usually associated with low intensity aurorae (Royrvik and Davis, 1977).

In this report an alternative interpretation is presented based on observations of wave-like density fluctuations in the neutral atmosphere. It is shown how variations of the precipitated flux can be caused by variations of the altitude at which the particles are lost, and how the magnitude of the flux variations is related to the form of the pitch angle distribution in the loss cone. The loss cone variations necessary to account for the observed features of auroral pulsations can be supplied by atmospheric acoustic-gravity waves similar to the waves that distort noctilucent cloud layers.

PRECIPITATION MODULATIONS FROM LOSS CONE VARIATIONS

The size of the loss cone is determined by the altitude at which particles are lost from the trapping region by atmospheric absorption (cf Roederer 1970). The maximum pitch angle in the loss cone is defined as the loss cone angle α_c . The loss cone angle effectively divides trapped and precipitating particles in the magnetosphere. From observations of radiation belt pitch angle distributions it is found that the pitch angle that mirrors at ~ 100 km altitude typically marks the boundary of trapped pitch angles; thus reference is frequently made to the "100 km loss cone."

Consider the situation illustrated in Fig. 1 where the altitude at which absorption occurs changes as a result of some modification of the atmosphere. Because the particle population throughout the magnetospheric flux tube does not instantly respond to a change in the loss cone at low altitudes, the distinction between trapped and precipitated pitch angles is temporarily upset. In particular, if the loss cone increases, some particles that were previously trapped will become members of the loss cone population. If the loss altitude is steadily increased over a period of time, sustained enhanced precipitation will occur throughout that period. A similar mechanism is in operation in the vicinity of the South Atlantic Anomaly (Paulikas, 1975, Torr et al 1976) where quasitrapped particles drift through a region of increasing local loss cone until they are absorbed. In the present case, however, the precipitation occurs by virtue of a temporally changing local

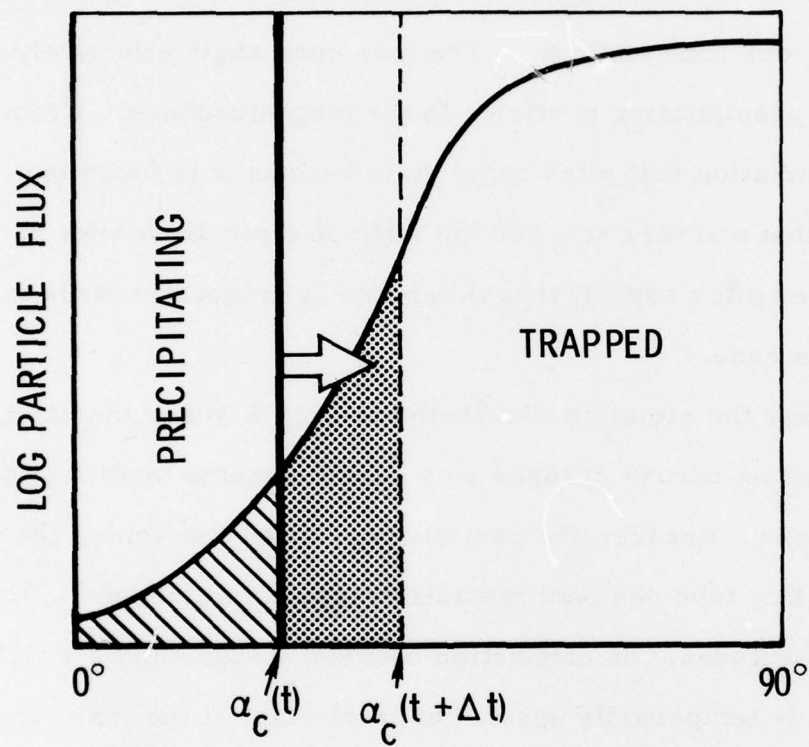


Fig. 1. Precipitation Enhanced by Increasing Loss Altitude That Produces an Increase in the Loss Cone Angle α_c

atmosphere density profile rather than by a spatially changing atmospheric density distribution that is experienced by azimuthally drifting particles.

Decreases in the size of the loss cone similarly cause decreases in precipitation. However, if the loss cone increases and then decreases sequentially, a more rigorous description of the magnetospheric particle response is required to obtain the time variations of the precipitated flux. Following Torr et. al. (1976), an equation that describes the temporal behavior of the loss cone population N of a magnetospheric flux tube can be written

$$\frac{dN}{dt} = Q - L \quad (1)$$

where Q represents sources and L represents the loss or precipitation rate. The source of particles, which is not understood in detail, probably operates at high altitudes where the atmosphere has little influence. If it is assumed that all changes in N are caused only by temporal changes in the atmospheric loss cone angle α_c , L is given by

$$L = Q - \left(\frac{dN}{d\alpha} \right)_{\alpha=\alpha_c} \frac{d\alpha_c}{dt} \quad (2)$$

Equation (2) provides a means of evaluating L , the rate at which particles in the flux tube are lost to the atmosphere.

In order to carry out a numerical investigation of precipitation variations, assumptions regarding the nature of the source Q , the pitch angle distribution $\frac{dN}{d\alpha}$ and the rate of change of the loss cone angle $\frac{d\alpha_c}{dt}$ are required. According to Kennel and Petschek (1966) the introduction of a midplane (ie equatorial) source in a magnetic trapping geometry wherein pitch angle diffusion is occurring leads to a mono-energetic pitch angle distribution at the loss cone angle given by

$$F(\alpha_c) = \frac{S}{D} \sqrt{DT} I_0(\alpha_c / \sqrt{DT}) / \alpha_c I_1(\alpha_c / \sqrt{DT}) \quad (3)$$

where I_0 and I_1 are the modified Bessel functions, S is related to the source strength, T is approximately equal to a quarter bounce period, and D is a constant that characterizes the strength of diffusion. Because the distribution (3) was derived under the assumption of a steady state, the quantity S is actually the rate at which particles enter the loss cone via the diffusion mechanism. Thus, Q in eq. (2) can be set equal to S . The appropriate value for $\left(\frac{dN}{d\alpha}\right)_{\alpha = \alpha_c}$ is then given by eq. (3).

Note that S enters eq. (2) as a normalization factor. The remaining quantity to be defined is $\frac{d\alpha_c}{dt}$.

Changes in the loss cone size are caused by changes in the altitude at which particles are lost to the atmosphere. The variations in the loss cone angle related to a particular perturbation of the loss altitude h can be approximated by

$$\alpha_c(t) = \sin^{-1} \left[\left(\frac{r_0}{r_0 + h(t)} \right)^3 \sin^2 \alpha_0 \right]^{1/2} \quad (4)$$

where r_0 and α_0 are values of the geocentric radius of the loss level and the loss cone angle at some reference point. The corresponding expression describing the loss cone rate of change $d\alpha_c / dt$ is

$$\frac{d\alpha_c}{dt} = \frac{3}{2} \tan \alpha_c \frac{dh(t)}{dt} \frac{1}{(r_0 + h(t))} \quad (5)$$

In the present calculations it is assumed that r_0 corresponds to the geocentric distance at 100 km altitude and that α_0 has a typical value of 1.5° which is the 100 km loss cone at $L \approx 9$. Three characteristic loss cone variations of interest are : 1) monotonically increasing α_c , 2) monotonically decreasing α_c , and 3) periodically varying α_c .

Figure 2a shows how L/S varies with time for a constantly increasing loss level described by

$$h(t) = At \quad (6)$$

for selected values of the parameters D , T and A .

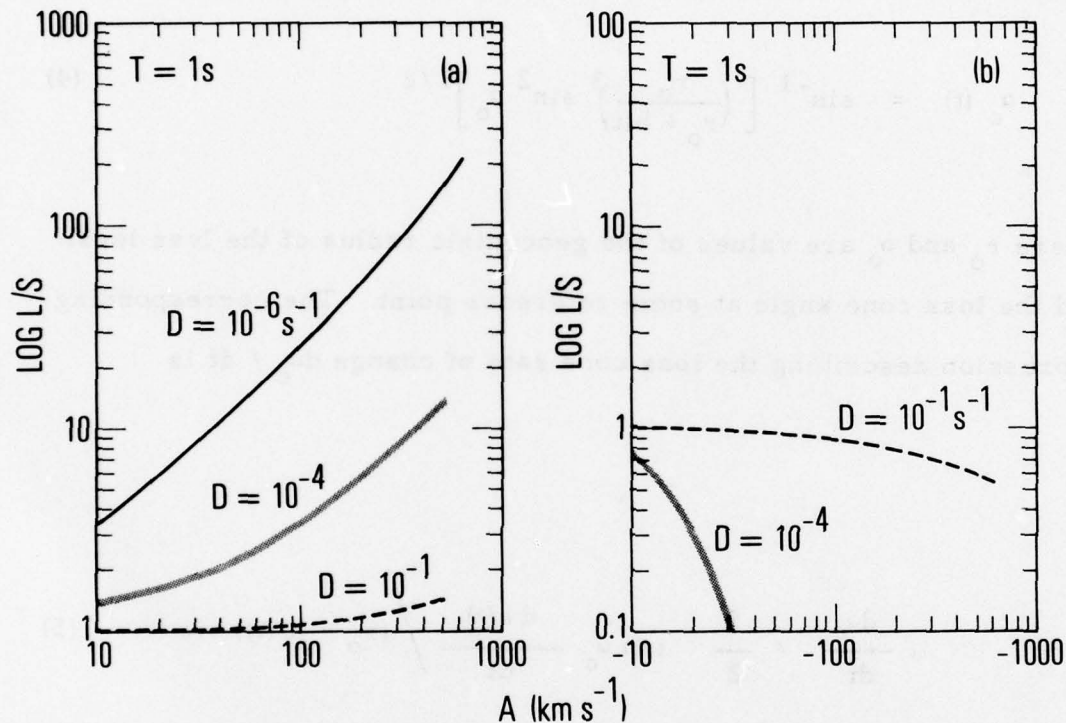


Fig. 2. (a) Variation of L/S Caused by a Loss Altitude That Constantly Increases at the Rate A . The parameter DT characterizes the shape of the pitch angle distribution of the precipitating particles. (b) Variation of L/S caused by a loss altitude that constantly decreases at the rate A .

It is seen that for a given value of A strong diffusion (large DT) produces a slower increase in the loss rate than weak diffusion (small DT). This behavior can be understood by considering the shape of the loss cone distribution (3). In strong diffusion the pitch angle distribution is nearly isotropic. As a result, a specific increase in the loss cone angle will increase the loss cone population by a smaller factor than the same increase in a distribution that rises rapidly outside of the loss cone. Pitch angle distributions associated with weak diffusion (small DT) possess the latter characteristic (cf Theodoridis and Paolini, 1967).

Figure 2b shows the analogous results for a decreasing loss cone corresponding to negative A values in eq. (6). Again, variations are enhanced when the value of DT is small. In this case, however, the decreasing bounce loss cone can produce changes in N that exceed the rate of supply by the source S , i. e. negative values of L are obtained from eq. (2). Since negative L/S simply means an absence of precipitation, these negative values are set equal to zero in Fig. 2b.

Periodic changes in the loss cone size can be caused by periodic changes in the altitude at which particles are lost to the atmosphere. Under this condition, variations in the loss cone angle can be obtained from eq. (4) with

$$h(t) = A \sin \omega t \quad (7)$$

Here A describes the amplitude of the altitude variation and ω is the frequency. Equation (5) gives the corresponding expression for $d\alpha_c / dt$:

$$\frac{d\alpha_c}{dt} = \frac{3}{2} A \omega \tan \alpha_c \cos \omega t / (r_o + A \sin \omega t) \quad (8)$$

Figure 3 shows some examples of the periodic variation of $\frac{L}{S}$ with time for selected values of the parameters D, T, A and ω . Two distinctive types of variations are apparent: quasisinusoidal and pulsed. Similar results are obtained for other combinations of D, T, A and ω . These two forms can be qualitatively explained by considering the dynamic competition between high altitude diffusion into the loss cone and the "windshield wiper" action of the atmosphere at the ends of the flux tube. If practically sinusoidal modulation occurs, the diffusion must be strong enough to produce a nearly isotropic pitch angle distribution. The variation of the loss cone population then virtually tracks the loss cone oscillations at low altitude. If pulsed modulations occur, diffusion is sufficiently weak that a significant density gradient exists at the loss cone angle. Precipitation is enhanced during the increasing phase of the loss cone cycle, and decreases as the loss cone shrinks, but in the latter phase the diffusion rate cannot replenish the newly trapped pitch angles fast enough to maintain the equilibrium distribution (3). As before, when the diffusion rate into the loss cone cannot keep up with the

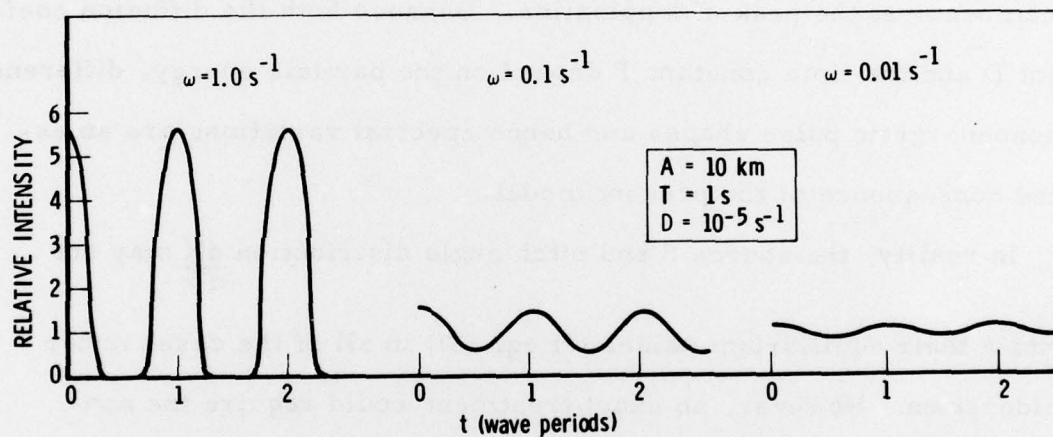


Fig. 3. Variation in L/S Produced by Sinusoidal Variations in the Loss Altitude. These pulsations occur for a variety of wave amplitudes A , frequencies ω , and diffusion parameters DT . Negative values of L/S have been set equal to zero.

rate at which loss cone particles can be lost, equation (2) gives negative values of L which have been set equal to zero in Fig 3 to indicate an absence of precipitation. The behavior in this case is similar to the response created by the rapid withdrawal of a piston in a container of gas; the strong diffusion case would correspond to a slowly withdrawn piston.

The energy spectrum of precipitating particles will vary during the cycle of a pulsation if the magnitude or form of the pulsations depends on the energy. Figure 4 illustrates how either spectral hardening or softening can occur at the peak of a pulsation. Because both the diffusion coefficient D and the time constant T depend on the particle energy, differences in monoenergetic pulse shapes and hence spectral variations are an expected consequence of the present model.

In reality, the source S and pitch angle distribution $\frac{dN}{d\alpha}$ may not maintain their equilibrium values (cf eq. (3)) in all of the cases under consideration. However, an exact treatment would require the non-trivial solution of the time dependent diffusion equation with a time dependent boundary condition at $\alpha = \alpha_c$. The qualitative behavior shown in Figs 2-3 is probably a good approximation provided that no instabilities associated with the loss cone variations modify the diffusion coefficient or the source.

ATMOSPHERIC WAVES AS SOURCE OF LOSS CONE VARIATIONS

Atmospheric pressure waves have been observed since the early sixties (cf Chrzanowski et al 1961, Campbell and Young, 1963). Wilson

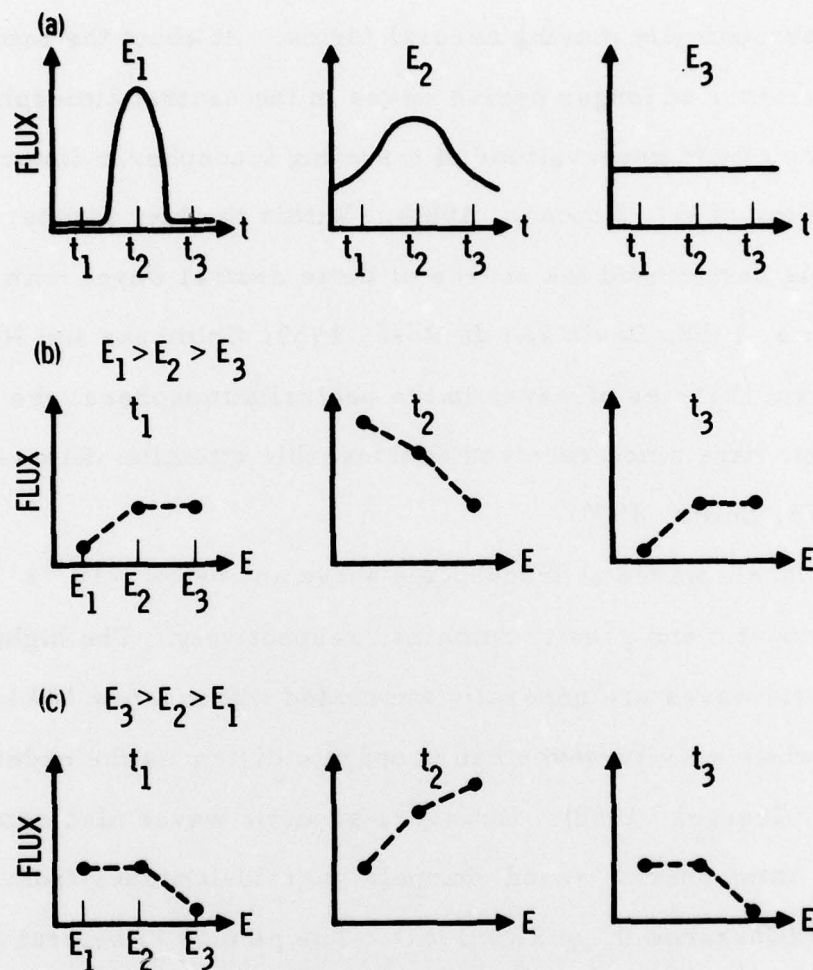


Fig. 4. (a) Three Different Precipitation Pulse Shapes at Three Energies. (b) Particle spectrum before pulse, at pulse peak, and after pulse when the energies E_1 , E_2 , and E_3 are ordered as shown. The spectrum softens at the pulse peak. (c) Particle spectrum before pulse, at pulse peak, and after pulse when energies E_1 , E_2 , and E_3 are ordered as shown. The spectrum hardens at the pulse peak.

(1967) proposed a shock wave model for the generation of infrasonic waves by supersonically moving auroral forms. At about the same time, the existence of longer period waves in the neutral atmosphere was established from observations of traveling ionospheric disturbances (TIDs) (eg. King, 1967, Bowman, 1968). Within the last decade, theoretical models have linked the source of these neutral waves with the aurora (Thorne, 1968, Davis and da Rosa, 1969, Chimonas and Hines, 1970). General theories of waves in the neutral atmosphere, the acoustic-gravity waves, have since received considerable attention (Hines, 1974, Francis, 1975, Smith, 1977).

Atmospheric waves at frequencies above and below $\sim 10^{-2} \text{ s}^{-1}$ belong to the acoustic and gravity domains, respectively. The higher frequency acoustic waves are generally attenuated within a few 100 km of the source, while gravity waves can propagate distances the order of an earth radius (Georges, 1968). However, acoustic waves also appear to propagate in atmospheric "sound channels" to mid-latitudes from the auroral zone (Chrzanowski et al., 1961). The picture of neutral waves that emerges from integrating theory and observation (Newton et al., 1969, Reber et al., 1975) is one in which wave-like corrugations of the isodensity surfaces of the atmosphere above ~ 80 km are generated by active auroral arcs and launched approximately along magnetic meridians with horizontal phase velocities equal to the local sound speed of $\sim 200 \text{ m s}^{-1}$. The wave amplitude expressed in terms of departure from the quiescent atmospheric density as given by standard model atmospheres is typically $\sim 15\%$ - 50% . Noctilucent cloud observations (Fogle and Haurwitz,

1966) indicate the presence of horizontal wavelengths at ~ 85 km altitude of $\sim 1 - 10$ km, while horizontal wavelengths of $\sim 100 - 1000$ km are inferred from TID's (Francis, 1975). The vertical extent or amplitude of these waves covers a wide range, but is often comparable to the horizontal wavelength.

Although the periods of gravity waves are much too long to explain the frequencies of typical auroral pulsations, acoustic waves with periods ~ 10 s are also present in the auroral zone atmosphere. The $\sim 1 - 10$ km wavelengths that are seen traveling horizontally at the sound speed in noctilucent cloud layers can provide the observed auroral pulsation frequencies. Moreover, as illustrated by Fig. 5, thermospheric winds which blow across the polar cap at velocities in excess of ~ 100 m s^{-1} (Meriwether et al., 1973, Brekke et al., 1974) can Doppler shift neutral waves to frequencies between ~ 0 and twice their natural frequency.

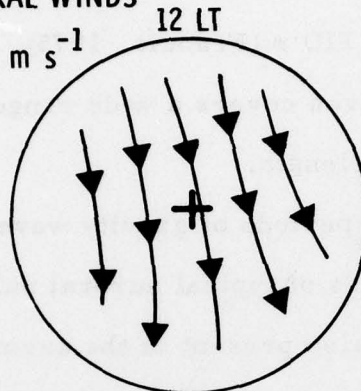
DISCUSSION

In view of the thesis of the paper, it is interesting to note that Porter et al. (1974) pointed out the possible connection between neutral waves and airglow intensity fluctuations. Auroral pulsations, on the other hand, have previously been considered as a prospective source of neutral waves (Maeda and Watanabe, 1964).

In the introduction a list of the observational properties of the pulsating aurora was given. This set of characteristics can now be reconsidered from the viewpoint of the present model. In fact, all of the listed observational features can be explained:

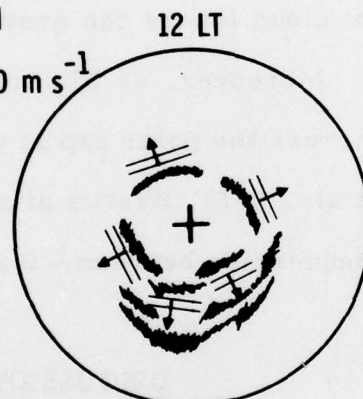
POLAR CAP NEUTRAL WINDS

$$|\bar{V}_{\text{wind}}| \approx 150-200 \text{ m s}^{-1}$$



ACOUSTIC-GRAVITY WAVE GENERATION

$$|\bar{V}_{\text{phase}}| \approx 200-300 \text{ m s}^{-1}$$



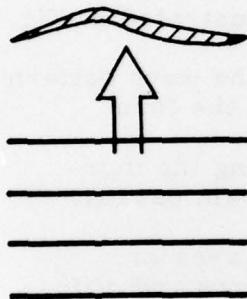
DOPPLER SHIFT

$$\omega_{\text{OBS}} = \frac{2\pi}{\lambda} (\bar{V}_{\text{phase}} + \bar{V}_{\text{wind}})$$

Fig. 5. Doppler Shift of Neutral Waves by Polar Cap Neutral Winds. The phase and wind velocities cancel on the dayside, while the velocities reinforce on the nightside where pulsations are observed.

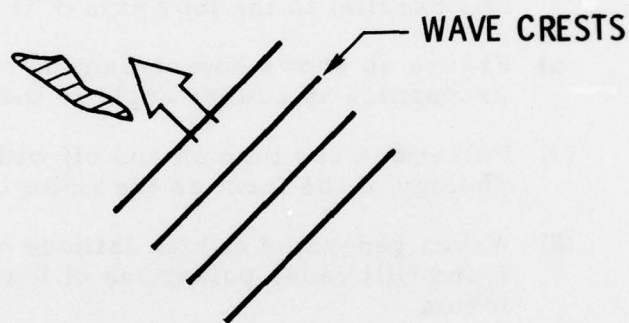
- (1) Figure 3 illustrates that both sinusoidal and pulsed precipitation can be driven by the passage of a sinusoidal wavetrain.
- (2) Damped pulsations correspond to damped waves; irregular pulsations can result from aperiodic local density fluctuations.
- (3) Pulse amplitudes within the framework of this model are virtually unlimited.
- (4) The periods of the precipitation variations are limited only by the frequency spectrum of the atmospheric density fluctuations and by the magnitude and direction of the local neutral wind velocity.
- (5) An entire form can pulsate synchronously if the wavefront lies parallel to the long axis of the form as illustrated in Fig. 6a.
- (6) Figure 6b shows how streaming can occur if the wave pattern propagates at a large angle to the long axis of the form.
- (7) Pulsations can turn on and off without disturbing the morphology of the form as the finite length wavetrain passes.
- (8) Waves generated at high latitude where active arcs are found will cause pulsations of lower latitude arcs and diffuse forms.
- (9) Pulsations will occur conjugately (within a bounce period) if backscatter is sufficiently intense and if the conjugate point atmosphere is not undergoing comparable oscillations.
- (10) The polar cap neutral wind pattern usually shows a strong afternoon quadrant to predawn quadrant alignment (cf Meriwether et al, 1973); only waves traveling equatorward in the vicinity of the predawn quadrant will be Doppler shifted to the frequencies that characterize auroral pulsations.
- (11) Precipitation caused by the oscillating atmosphere depends on the particle diffusion coefficient D and quarter bounce time T (ie. on the pitch angle distribution determined at high altitude) which are energy dependent; thus, the pulsations will be different at different energies. The largest fractional fluctuations are associated with weak diffusion or mirroring pitch angle distributions. Distributions peaked at 90° have been observed by Whalen et al (1975) near a pulsating aurora.

SYNCHRONOUS
PULSATION



(a)

STREAMING



(b)

Fig. 6. (a) Synchronous Pulsations That Can Occur If the Wavefront Lies Parallel to the Auroral Arc. (b) Streaming that can be caused by a wavefront traveling perpendicular to the long axis of an auroral form.

The model for the pulsating aurora proposed here is by no means complete. In particular, the morphology of neutral waves at $\sim 85 - 100$ km altitude where the auroral emissions are generated can only be inferred from observations of noctilucent clouds. However, as indicated by the foregoing list, the model can at least conceptually account for a large number of the experimentally determined characteristics of auroral pulsations.

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